

**\*\*TITLE\*\***

*ASP Conference Series, Vol. \*\*VOLUME\*\*, \*\*PUBLICATION YEAR\*\**

**\*\*EDITORS\*\***

### 3-D General Relativistic MHD Simulations of Generating Jets

K.-I. Nishikawa

*Rutgers University, Department of Physics and Astronomy, Piscataway, NJ 08854-8019, USA*

S. Koide

*Toyama University, Faculty of Engineering, 3190 Gofuku, Toyama 930-8555, Japan*

K. Shibata

*Kyoto University, Kwasan Observatory, Yamashina, Kyoto 607-8471, Japan*

T. Kudoh

*National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan*

H. Sol

*DARC, Observatoire de Paris-Meudon, 92195 Meudon Cedex, France*

**Abstract.** We have performed a first fully 3-D GRMHD simulation with Schwarzschild black hole with a free falling corona. The initial simulation results show that a jet is created as in previous axisymmetric simulations. However, the time to generate the jet is longer than in the 2-D simulations. We expect that due to the additional azimuthal dimension the dynamics of jet formation can be modified.

## 1. Introduction

Relativistic jets have been observed in active galactic nuclei (AGNs) and microquasars in our Galaxy, and it is believed that they originate from the regions near accreting black holes. To investigate the dynamics of accretion disks and the associated jet formation, we use our newly developed full 3-D GRMHD code.

Recently, Koide, Shibata, & Kudoh (1999) have investigated the dynamics of an accretion disk initially threaded by a uniform poloidal magnetic field in a non-rotating corona (either in a state of steady fall or in hydrostatic equilibrium) around a non-rotating black hole. The numerical results show that the disk loses angular momentum by magnetic braking, then falls into the black hole. The infalling motion of the disk, which is faster than in the non-relativistic case because of the general-relativistic effect below  $3r_S$  ( $r_S$  is the Schwarzschild radius), is strongly decelerated at the shock formed by the centrifugal force around

$r = 2r_S$  by the rotation of the disk. Plasmas near the shock are accelerated by the  $\mathbf{J} \times \mathbf{B}$  force, which forms bipolar relativistic jets. Inside this *magnetically driven jet*, the gradient of gas pressure also generates a jet over the shock region (*gas-pressure-driven jet*). This *two-layered jet structure* is formed both in a hydrostatic corona and in a steady-state falling corona. Koide et al. (2000) have also developed a new GRMHD code in Kerr geometry and have found that, with a rapidly rotating ( $a = 0.95$ ) black-hole magnetosphere, the maximum velocity of the jet is  $0.9\,c$  and its terminal velocity  $0.85\,c$ . All of the previous 2-D GRMHD simulations described here were made assuming axisymmetry with respect to the  $z$ -axis and mirror symmetry with respect to the plane  $z = 0$ ; the axisymmetric assumption suppressed the azimuthal instabilities.

## 2. 3-D GRMHD Simulations: Equations and Numerical Techniques

Our basic equations are those of Maxwell for the fields and a set of general-relativistic equations representing the plasma, namely the equations of conservation of mass, momentum, and energy for a single-component conducting fluid (Weinberg 1972; Thorne et al. 1986). In making the simulations, we use these equations with the 3+1 formalism (for details, see Koide, Shibata, & Kudoh 1999).

## 3. Preliminary 3-D GRMHD simulations with a Schwarzschild black hole

In order to investigate how accretion disks near black holes evolve under the influence of accretion instabilities such as the magnetorotational instability, the use of a fully 3-D GRMHD is essential.

### 3.1. Initial and boundary conditions

In the assumed initial state, the simulation region is divided into two parts: a background corona around a black hole, and an accretion disk (Fig. 1a and 1b). The coronal plasma is set in a state of transonic free-fall flow, as in the case of the transonic flows with  $\Gamma = 5/3$  and  $H = 1.3$ ; here the sonic point is located at  $r = 1.6r_S$ . The Keplerian disk in the corona is set in the following way. The disk region is located at  $r > r_D \equiv 3r_S, |\cos\theta| < \delta = 1/8$ . Here the density is 100 times that of the background corona (Fig. 1a), while the orbital velocity is relativistic and purely azimuthal:  $v_\phi = v_K \equiv c/[2(r/r_S - 1)]^{1/2}$ . (Note that this equation reduces to the Newtonian Keplerian velocity  $v_\phi = \sqrt{GM/r}$  in the non-relativistic limit  $r_S/r \ll 1$ ). The pressure of both the corona and the disk are assumed equal to that of the transonic solution. The initial conditions for the entire plasma around the black hole are:

$$\rho = \rho_{\text{ffc}} + \rho_{\text{dis}} \quad (1)$$

$$\rho_{\text{dis}} = \begin{cases} 100\rho_{\text{ffc}} & (r > r_D \quad \text{and} \quad |\cot\theta| < \delta) \\ 0 & (r \leq r_D \quad \text{or} \quad |\cot\theta| \geq \delta) \end{cases} \quad (2)$$

$$(v_r, v_\theta, v_\phi) = \begin{cases} (0, 0, v_K) & (r > r_D \text{ and } |\cot\theta| < \delta) \\ (-v_{\text{ffc}}, 0, 0) & (r \leq r_D \text{ or } |\cot\theta| \geq \delta) \end{cases} \quad (3)$$

where we set  $\delta = 0.125$ ; the smoothing length is  $0.3r_S$ .

In addition, there is a magnetic field crossing the accretion disk perpendicularly. We set it to the Wald solution (Wald 1974), which represents the uniform magnetic field around a Kerr black hole:  $B_r = B_0 \cos\theta$ ,  $B_\theta = -\alpha B_0 \sin\theta$  (where  $\alpha$  is the lapse function,  $\alpha = (1 - r_S/r)^{1/2}$ ). At the inner edge of the accretion disk, the proper Alfvén velocity is  $v_A = 0.015c$  in a typical case with  $B_0 = 0.3\sqrt{\rho_0 c^2}$ , where the Alfvén velocity in the fiducial observer

$$v_A \equiv B/\sqrt{\rho + [\Gamma p/(\Gamma - 1) + B^2]/c^2}. \quad (4)$$

The plasma beta of the corona at  $r = 3r_S$  is  $\beta \equiv p/B^2 = 1.40$ . The simulation is performed in the region  $1.1r_S \leq r \leq 20r_S$ ,  $0 \leq \theta \leq \pi$ ,  $0 \leq \phi \leq 2\pi$  with  $100 \times 120 \times 60$  meshes. The effective linear mesh widths at  $r = 1.1r_S$  and at  $r = 20r_S$  are  $5.38 \times 10^{-3}r_S$  and  $0.97r_S$ , respectively, while the angular spacings along the polar and azimuthal directions are  $5.2 \times 10^{-2}$  rad. A radiative boundary condition is imposed at  $r = 1.1r_S$  and at  $r = 20r_S$ :

$$u_0^{n+1} = u_0^n + u_1^{n+1} - u_1^n, \quad (5)$$

where the superscripts  $n+1$  and  $n$  denote the time steps and the subscripts 0 and 1 refer to the boundary and to its neighbor meshes, respectively. The computations were made on an ORIGIN 2000 computer with 0.898 GB internal memory, and they used about 47 hours of CPU time for 10000 time steps with  $100 \times 120 \times 60$  meshes.

### 3.2. Simulation results

Figure 1 shows the evolution of 3-D simulation performed in the region  $1.1r_S \leq r \leq 20r_S$ ,  $0 \leq \theta \leq \pi$ , and  $0 \leq \phi \leq 2\pi$  with  $100 \times 120 \times 60$  meshes. The parameters used in this simulation are the same as those of the axisymmetric simulations shown in Fig. 6 of Koide, Shibata, & Kudoh (1999). In this figure, the colored shading shows the proper mass density ((a) and (c)) and the pressure ((b) and (d)) on logarithmic scales; the vector plots show the magnetic field ((a) and (c)) and flow velocity ((b) and (d)).

The black circle represents the black hole. Figures 1a and 1b present the initial conditions, which are the same as in the 2-D simulations (Koide, Shibata, & Kudoh 1999). At  $t = 39.2\tau_S$  comparing with Fig. 6c ( $t = 40.0\tau_S$ ) in Koide et al. (1999) the jet is less generated. At  $t = 60.0\tau_S$  the jet is generated as 2-D simulation at the earlier time ( $t = 40.0\tau_S$ ). At  $t = 73.9\tau_S$ , the jet is clearly created around  $r = 4.5r_S$ , which is shown by the enhanced density (Fig. 1c) and pressure (Fig. 1d). As in the 2-D simulations the jet is generated in a hollowed cylindrical form. The magnetic field is twisted by the accretion disk and pinched, which increases the magnetic field pressure and generates the jet near the black hole. The delay of jet formation seems to be due to reduction of shock formation at  $r = 2r_S$  caused by the additional freedom in the azimuthal direction. Further investigation will be reported elsewhere.

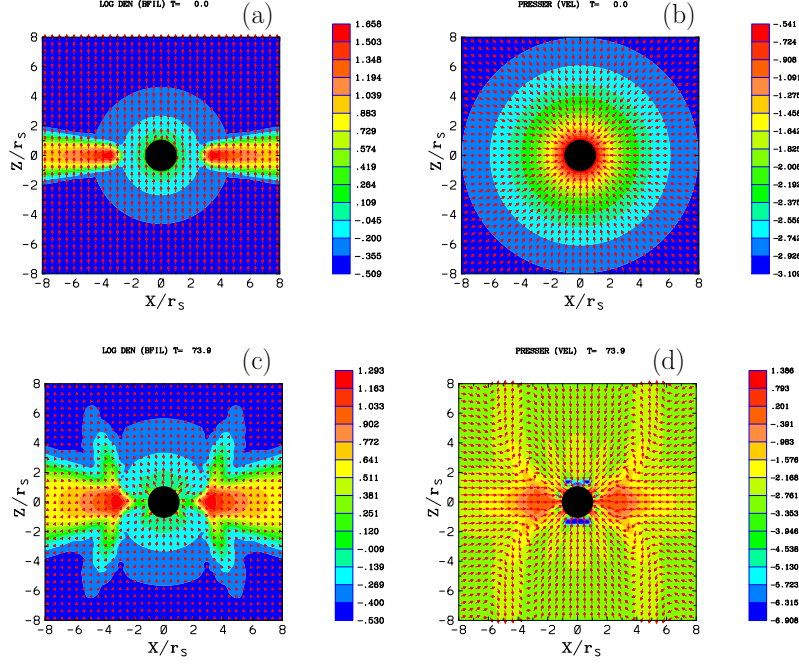


Figure 1. For the fully 3-D simulation, these panels present the time evolution of the proper mass density with the magnetic field ( $B_x, B_z$ ) ((a) and (c)) and the proper pressure with the flow velocity ( $v_x, v_z$ ) ((b) and (d)) in a transonic free-fall (steady-state falling) corona with an initially uniform magnetic field, at  $t = 0.0\tau_S$  ((a) and (b)), and  $t = 73.9\tau_S$  ((c) and (d)). The jet is formed around  $r = 4.5r_S$  as in the 2-D simulation.

#### 4. Discussion

This simulation result is initial and we will perform more simulations and investigate effects of the third dimension. Further results will be reported elsewhere. K.N. is partially supported by NSF ATM 9730230, ATM-9870072, ATM-0100997, and INT-9981508. The simulations have been performed on ORIGIN 2000 at NCSA which is supported by NSF.

#### References

- Koide, S., Shibata, K., & Kudoh, T. 1999, ApJ, 522, 727
- Koide, S., Meier, D. L., Shibata, K., & Kudoh, T. 2000, ApJ, 536, 668
- Thorne, K. S., Price, R. H., & Macdonald, D. A. 1986, Black Holes: The Membrane Paradigm (New Haven: Yale Univ. Press)
- Wald, R. M. 1974, Phys.Rev.D, 10, 1680
- Weinberg, S. 1972, Gravitation and Cosmology (New York: Wiley)